Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

(1) 5C

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER (14) AFGL-TR-80-0257	2. GOVT ACCESSION NO. AD-A092 335	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) INTERFEROMETRIC DETERMINATIONS OF ASTEROID DIAMETERS		5. TYPE OF REPORT & PERIOD COVERED Scientific. Interim.
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) S. P. Worden (12) 14		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Geophysics Laboratory (PHS) Hanscom AFB Massachusetts 01731 61102F		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS (16) 2311G311 (17) G3
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Geophysics Laboratory (PHS) Hanscom AFB Massachusetts 01731		12. REPORT DATE 10 September 1980
		13. NUMBER OF PAGES 13
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) (11) 1979		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

~~Approved for public release; distribution unlimited.~~

DTIC ELECTE NOV 6 1980 S D B

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Reprinted from Asteroids (Ed: T. Gehrels), Tucson, U. Arizona Press, p. 119, December 1979

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Speckle interferometry
Asteroids
Minor planets

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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AFGL-TR-80-0257

INTERFEROMETRIC DETERMINATIONS OF ASTEROID DIAMETERS

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A promising Earth-based technique for directly determining diameters of asteroids is based on new developments in interferometry. Until 1978 application of interferometric techniques to asteroids was limited to the very brightest objects by the low sensitivity of available detectors. Results have been published only for Pallas and Vesta. However, modern photoelectric detectors are now being used in these observations and diameter measurements for a number of minor planets will be forthcoming.

The resolution of optical telescopes is classically given by the Rayleigh criterion and is inversely proportional to the telescope diameter. However, as is well known, turbulence in the earth's atmosphere or "seeing" degrades virtually all telescope images to about one arcsec. Since the largest asteroid angular diameters are about 0.5 arc sec. conventional telescope images are limited for measuring asteroid sizes and shapes. In principle, telescopes of 4–5 meter diamter not limited by seeing could obtain angular resolution of 0.02 arcsec. translating into about 30-km resolution in the asteroid belt.

Recent techniques, speckle and amplitude interferometry (or single aperture interferometry) offer great promise for removing the degrading effects of the atmosphere. Interferometry was first employed to measure the diameter of the asteroid Vesta by Hamy in about 1899 (see Dollfus 1971). In 1977 Vesta and Pallas were observed by Worden *et al.* (1977) and later by

Worden and Stein (1979) using speckle interferometry, but extension of this work to fainter asteroids has been hindered by the low sensitivity of available detectors. With suitable application of these methods it now appears possible to directly measure angular sizes and even produce images for several hundreds of the larger asteroids. In this chapter I discuss the limited work already done on asteroids with speckle interferometry and more extensive work in progress to apply single aperture interferometry to asteroid studies.

I. SPECKLE INTERFEROMETRY

Small-scale temperature inhomogeneities in the earth's atmosphere produce changes in the index of refraction. These refractive index changes cause phase delays along an incoming plane wave, which may be light from a stellar point source. This is represented schematically in Fig. 1. Without phase errors, optical systems produce the image shown in Fig. 1*A*, which is said to be "diffraction limited," where a point-source image is the classical Airy disk for a circular telescope aperture. The size of this image is inversely proportional to the telescope diameter. With any phase errors telescope resolution is degraded to that appropriate for an optical system only as large as the scale over which there is some phase coherence (i.e., the phase is the same). Since the atmosphere breaks an incoming plane wave into about 10-cm fragments, all telescopes produce images with resolution no better than that of a 10-cm telescope, namely one arcsec. This process is shown in Fig. 1*B*.

Labeyrie (1970) proposed a method to recover some information down to large telescope diffraction limits. He pointed out that short-exposure ($\Delta t \approx$ 0.01 sec) photos "freeze" the turbulence in the atmosphere. Although the phase coherence size in this "frozen" system is still only 10 cm, there will be some 10-cm patches scattered over the entire aperture which are at the same phase. These portions act in concert as a form of "multiple" aperture interferometer which provides some information down to the diffraction limit of the *entire* telescope aperture. As shown in Figure 1*C*, the image of a point source seen through a multiple-aperture interferometer is a series of nearly diffraction-limited images modulated by a one arcsec seeing disk. This process is known as "speckle interferometry" since the short-exposure photos, as shown in Fig. 2, look like laser speckle photos.

II. AMPLITUDE INTERFEROMETRY

An alternate approach to stellar interferometry, suggested by Currie (1967) and Currie *et al.* (1974), is similar to Michelson interferometry. Known as "amplitude interferometry," this technique uses a device like that shown in Fig. 3. The individual collection apertures are smaller than the 10-cm coherence length in order to reduce the correction due to atmospheric degradation to a negligible level. As the atmosphere modulates the relative

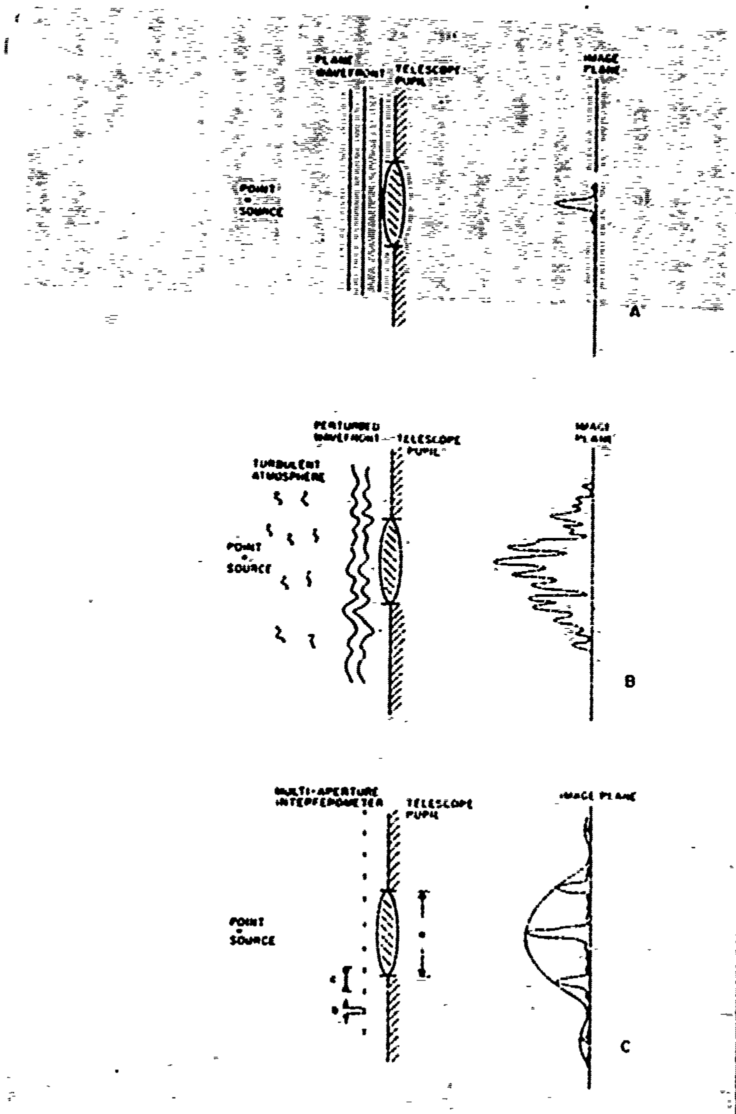

Fig. 1. Schematic diagram of image formation through a turbulent atmosphere: (A) diffraction-limited optics, no atmospheric turbulence; (B) image formation through a turbulent atmosphere; and (C) multiple-aperture interferometer.

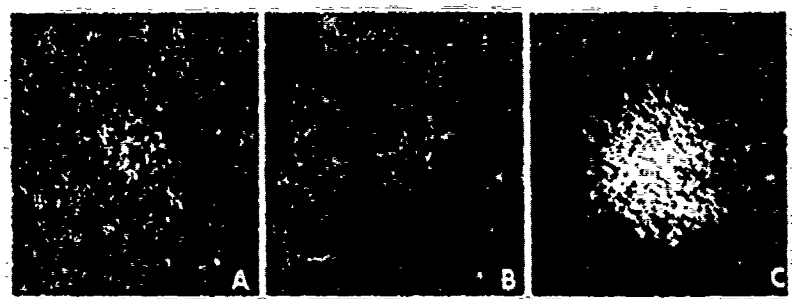

Fig. 2. Speckle photos from the Kitt Peak 4-m telescope. Each image is about 1 arcsec in extent. (A) α Orionis, a resolved supergiant star, (B) γ Orionis, a point-source star, and (C) α Aurigae, a binary star with 0.05-arcsec separation.

phase shifts between these two apertures, the coherence properties (and thus angular size) of the object as it appears outside the atmosphere can be learned. To obtain complete two-dimensional size and shape information the observer varies the separation and position angle for the two apertures. Currie has proposed and built a multiple-aperture amplitude interferometer system, that allows the full telescope aperture to be covered simultaneously and all Fourier components sampled simultaneously. The efficiency of such a system should be comparable to a speckle interferometry system.

III. DATA RECORDING SYSTEMS AND DATA REDUCTION TECHNIQUES

A diagram of the Kitt Peak photographic speckle interferometer is shown in Fig. 4. There are about six similar systems in use at the present time. The Kitt Peak camera was designed by Lynds (Lynds *et al.* 1976; Breckinridge *et*

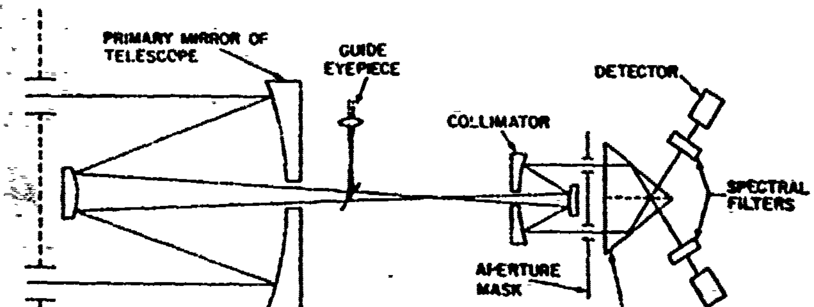

Fig. 3. Diagram of Currie's amplitude interferometer.

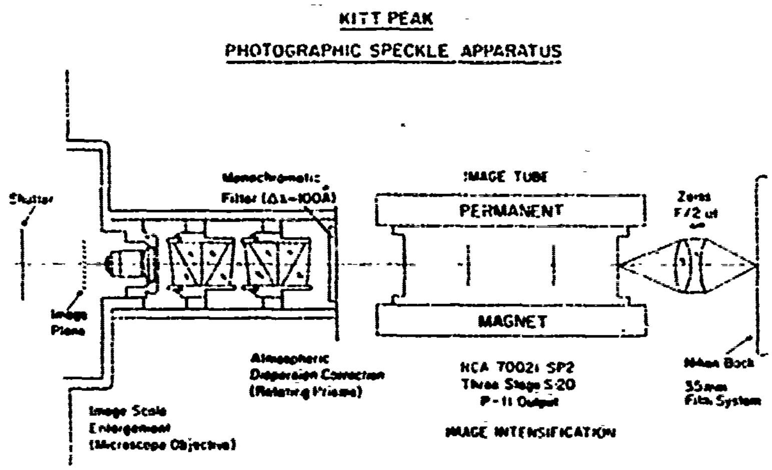

Fig. 4. Diagram of Lynds' speckle interferometer.

al. 1978). As shown in the figure, light from the telescope passes through a shutter and focuses at the telescope image plane. The shutter is necessary to insure exposures shorter than the atmospheric change time, typically 20 msec. The telescope image is relayed and magnified by a microscope objective. The magnification is set to provide a pixel resolution oversampling the telescope diffraction spot size by at least a factor of four. For the Kitt Peak 4-m telescope, this provides a final image scale of 0.2 arcsec/mm. Atmospheric dispersion blurs speckle image patterns in the sense that the "red" portion of the image focuses at a slightly different position than the "blue" portion. Since this may be significant for even 200 Å bandpass photos, a set of rotating atmospheric-compensating prisms is included to counteract the dispersion. Since there are about 20 orders of optical interference across a speckle photo, a narrow band ($\Delta\lambda \approx 200$ Å) interference filter is used to preserve coherence across the entire speckle photo. If this were not included, the "speckles" near the edge of the photos would be elongated. A three-stage image tube intensifies the image enough to allow photographic data recording. A transfer lens relays the intensified image to a data recording system, in this case a 35-mm film camera.

The speckle photos in Fig. 2 were taken with the Kitt Peak system. The different character of these photos is readily apparent. This is understandable from the analogy to a multiple-aperture interferometer. Each speckle should be a diffraction-limited image of the object. Indeed, the binary star (α Aur) speckles are double, the point-source speckles roughly diffraction spots, and the resolved star (α Ori) speckles somewhat larger. This aspect led Lynds *et al.* to a direct speckle image reconstruction scheme whereby individual speckles were identified and co-added to produce a nearly diffraction-limited image for the special case of stars like α Ori.

A number of methods exist to reduce speckle interferometry data. Labeyrie's (1970) original method is widely used, in particular for binary star measurements. Individual speckle photos are Fourier transformed either optically or digitally and the Fourier modulus computed. If the speckle image is represented in one dimension as $i(x)$, and its transform as $I(s)$, this process is mathematically represented by

$$I(s) = \int_{-\infty}^{\infty} i(x)e^{-2\pi ixs}dx. \tag{1}$$

The modulus or power spectrum, $|I(s)|^2$, of this transform contains the diffraction-limited information in an easily extractable form. In the case of the binaries, power spectra show banding which represents the binary separation; the wider the bands are apart, the closer the binary separation. The orientation of these bands represents the position angle of the binary system.

The residual effects of the seeing must be removed to yield the maximum accuracy. Even though the bands (fringes) are readily visible in raw speckle power spectra, their spacing is affected by the residual seeing effects. Labeyrie's method uses observation of point-source stars to determine these seeing effects and remove them. If $P_i(x)$ are point-source speckle photos with a mean power spectrum $\langle|P(s)|^2\rangle$, and $\langle|I(s)|^2\rangle$ the mean power spectrum of the object photos $i_i(x)$, then the diffraction-limited power spectrum of the object is given by

$$|O(s)|^2 = \frac{\langle|I(s)|^2\rangle}{\langle|P(s)|^2\rangle}. \tag{2}$$

Point-source data are usually derived from speckle observations of point-source stars situated near the program objects on the sky. Since these point-source objects are not in general observed within the same isoplanatic angle and not at the same time, their power spectrum can only represent the residual seeing effects in a statistical sense.

Worden *et al.* (1977) have developed a method to calibrate for residual seeing effects using the same set of speckle photos as used to study the program objects. We illustrate this method in Fig. 5. The method proceeds as follows: the mean autocorrelation function of a series of speckle, $i_i(x)$ photos is computed:

$$\begin{aligned} \langle AC(\Delta x)\rangle &= \left\langle \int_{-\infty}^{\infty} i_i(x) \cdot i_i(x-\Delta x)dx \right\rangle \\ &= \langle i_i(x) \star i_i(x) \rangle . \end{aligned} \tag{3}$$

(The autocorrelation is the Fourier transform of the power spectrum: see Bracewell 1965 for details.) As we see in Fig. 5, the mean autocorrelations are

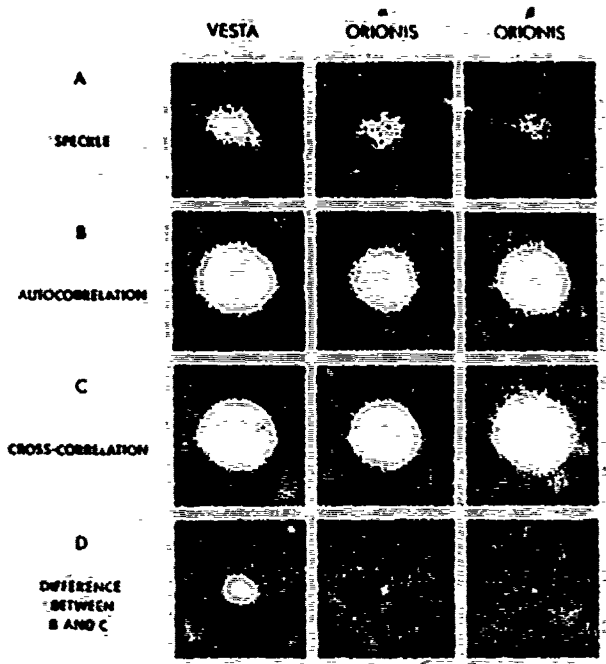

Fig. 5. Illustration of the Worden *et al.* (1977) method for reducing speckle interferometry data.

dominated by the seeing background. This background may be accurately removed by computing and subtracting the mean cross-correlation *between* consecutive speckle photos of the *same* set of data used to compute the autocorrelation. The cross-correlation (XC) between the i^{th} and $i^{th} + 1$ speckle photo is given by

$$\langle XC(\Delta x)\rangle = \left\langle \int_{-\infty}^{\infty} i_i(x) \cdot i_{i+1}(x-\Delta x)\,dx \right\rangle$$

$$= \langle i_i(x) \star i_{i+1}(x) \rangle . \qquad (4)$$

Welter and Worden (1978) showed that the resulting subtraction is the object autocorrelation as it would appear with virtually all seeing effects removed. This "diffraction-limited" autocorrelation contains information on such quantities as angular diameter in easily extractable form. For example, the angular diameter of an asteroid is simply the distance between the autocorrelation maximum and the point where the autocorrelation falls to zero.

Current photographic speckle cameras are generally limited to objects brighter than +7 mag. The photographic recording systems are therefore being replaced with high quantum efficiency digital recording systems. The University of Arizona speckle camera uses a Charge Injected Device (CID) television system to record photon arrivals. This system simply replaces the photographic emulsion, and it can record data for objects faint enough so that only a few photons arrive in a 20-msec exposure. In Fig. 6 we show data from this system for Saturn's moon Rhea, which is a 10^{th}-magnitude object. The limiting requirement for this method is that at least two photons lie in the same speckle. If we can record two photons per frame in a 20-msec exposure in some of the frames these two photons will lie in the same speckle and contribute to our diffraction limited signal. This translates to about a +16 stellar magnitude limit. Although angular diameters are more difficult to derive than binary separations, we have used this system to derive angular diameters for a 10.5 magnitude object (Iapetus) accurate to ± 5% with less than five minutes total observing time.

The amplitude interferometer obtains the high angular resolution information in a somewhat different fashion than the speckle interferometer. In this case, the light is sampled at the entrance aperture of the telescope, where the effect of the atmosphere has been to introduce only an error in the phase delay. The light from two separate apertures on opposite sides of the telescope is then interferometrically combined, as shown in Fig. 3.

In order to permit the observation of fainter objects, we wish to simultaneously use all the light entering the telescope aperture, i.e., the data from many thousands of pairs of apertures (a Multiple Aperture Amplitude Interferometer or MAAI). This may be done by replacing each of the two photomultipliers with a "television camera" in which each resolution element acts as a separate channel interferometer.

Results on solar system objects have been limited, largely due to the bright limiting magnitude of existing photographic speckle systems and amplitude interferometers. With the advent of efficient photoelectric and television systems this situation is changing. Table I lists data published on the asteroids Vesta and Pallas (Worden *et al.* 1977; Worden and Stein 1978). In these diameter determinations, circular objects, uniform albedo, and no limb darkening have been assumed. With a photographic limiting magnitude of +7, Vesta and Pallas are the only asteroids which have been observable so far. Amplitude interferometry has had an even more stringent limit, about +3 mag. I note that the speckle results for Vesta match other values for that asteroid's diameter very well, although Pallas' diameter is about 25% larger than the accurate occultation results for this object (Wasserman *et al.* 1979; see the chapter by Millis and Elliott). However, as alluded to earlier, photoelectric systems now make it possible to observe objects as faint as stellar magnitude +16.

We have used a prototype television system (Strittmatter and Woolf

TABLE I

Diameters of Solar System Objects from Speckle Interferometry

Object	Date (UT)	Angular Diameter (arcsec)	Diameter (km)
Vesta	1 Dec 76	0.400 ± 0.040	513 ± 51
Vesta	3 Feb 77	0.470 ± 0.020	550 ± 23
Pallas	3 Feb 77	0.730 ± 0.060	673 ± 55
Rhea	17 Apr 78	0.234 ± 0.005	1487 ± 40
Iapetus	17 Apr 78	0.189 ± 0.021	1200 ± 132

1978) on Steward Observatory's 2.3-m telescope to observe Saturn's satellites Rhea (~9.5 mag) and Iapetus (~10.5 mag). Figure 6 shows a speckle photograph from this system for Rhea: individual photon events are readily apparent. The angular diameters of these objects are listed in Table I. These values match lunar occultation values quite well (Elliot *et al.* 1975). A system developed by Boksenberg at the University College London has been used to

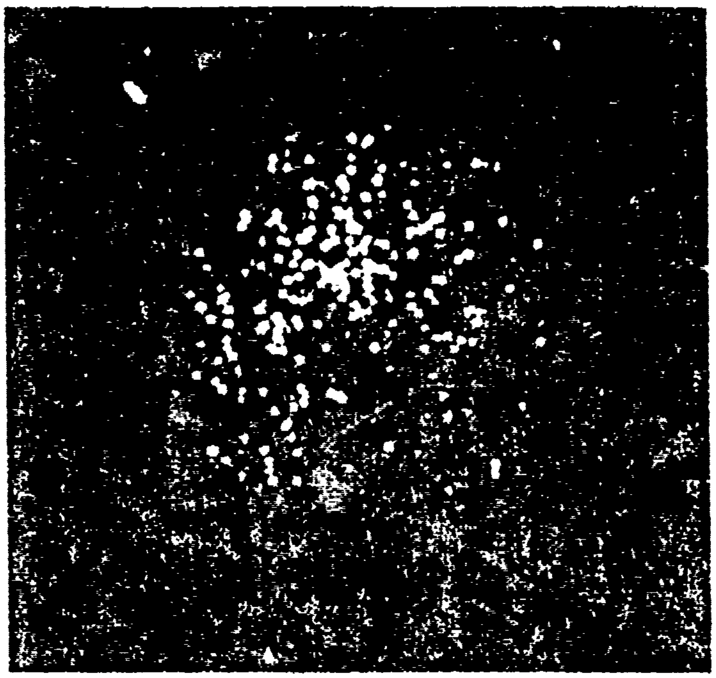

Fig. 6. Speckle data obtained with a digital camera for Rhea showing individual photons.

observe the asteroids 511 Davida and 40 Harmonia at about stellar magnitudes +11.5 and +12, respectively. Although these results have not been accurately calibrated yet, the ratio of the two objects' diameters of about 3, reported by other investigators, is confirmed.

The accuracies reported in Table I exceed the telescope diffraction limits by a significant factor. The quoted errors are based on diameter determinations from independent subsets of the data. The diameters themselves are derived by convolving various diameter asteroid profiles with point source speckle data obtained at the same time until a best match with the observed asteroid speckle profile is reached. Stellar diameters accurate to ± 3% internal error have been derived in this manner for objects close to the diffraction limit in size (Worden 1975) and diameters for objects considerably smaller than the diffraction limit are accurate to ± 30% (Worden 1976). These high precisions follow directly from the fact that the half width of Gaussian or other similar profile may be determined very accurately. As discussed by Worden (1976), this accuracy is considerably greater than the telescope diffraction limit. This problem is somewhat analogous to the ability of stellar astrometrists to measure star positions far more accurately than the half width of a stellar seeing disk.

There are, however, sources of systematic error in interferometric asteroid diameters, the assumption of uniform albedo, no limb darkening and spherical shape being among the most serious. Based on our stellar speckle results (Welter and Worden 1979), up to a 20% increase in angular diameter results from a fully limb darkened disk as compared to a uniform disk. However, based on space probe planetary and satellite images obtained to date, large limb darkening is highly unlikely. Indeed, as shown by McDonnell and Bates (1976) limb darkening may be a free parameter to be fit in the diameter fitting procedure described above, given accurate enough speckle data. In a similar manner other parameters such as elongated shape may be fit. Occultation results for Pallas show some elongation, so it will be necessary in future work to consider the effects of parameters other than uniform disk diameter. Until we have perfected these methods, interferometric diameters represent only the diameter of a uniform sphere which would produce the same light as the asteroid being observed. The accuracies reported therefore refer to our ability to determine this useful, but not complete parameter. To fully assess errors caused by this assumption we ultimately require actual high resolution images of each asteroid being studied.

The exciting new possibility of actual reconstructed images for asteroids appears to be within grasp. The methods for reducing data discussed above produce only a power spectrum or Fourier amplitude of the true image. Although size and shape may be derived from the Fourier amplitude, the Fourier phase is needed to reconstruct actual images. Several schemes have been developed to estimate the phase, (Bates 1978; Baldwin and Warner 1978) the most promising having recently been proposed by Fienup (1978).

The method involves an iterative scheme to guess phase values and determine whether the resulting image is consistent (i.e., all values positive and the object has a diameter matching the known value). We have tried this method on our power spectrum results from photographic Vesta data. With a 4-m telescope, a diffraction-limited image of Vesta would have over 100 resolution elements. The resulting image shown in Fig. 7, has the right diameter. This is encouraging since the diameter is a free parameter in Fienup's method as it is applied here. The mean noise in this image is ±3%, based on several sets of data taken within five minutes. We see no surface structure larger than this, although this is not a stringent limit. We do see a slight elongation with the long axis along position angle 16° ± 4° relative to east-west. The diameter ratio from the longest to shortest seems to be 1.19 ± 0.02. The reality of this elongation is open to question since polarimetric results (Gradie *et al.* 1978) indicate Vesta is spherical. Moreover, while the derived elongation is 20%, other speckle results from Kitt Peak often show up to a 10% elongation. We must therefore regard this image as a very preliminary attempt at asteroid imaging. Nonetheless, it is an encouraging development which clearly warrants further study.

Another promising aspect of interferometric methods is the possibility of

Fig. 7. Reconstructed image for Vesta from 3 February 1977 4-m Kitt Peak speckle data. The asteroid disk is 0.470 arcsec in diameter.

detecting close asteroid pairs. Binary star speckle has already been demonstrated for objects as faint as +12 mag by our group at the University of Arizona. It may therefore be possible to detect asteroid satellites using interferometric methods and work is now underway to accomplish this.

There are several limitations to interferometric methods. The +16-mag limit is set by the requirement of at least two photons per frame in a 0.01-sec exposure. To make interferometric methods work at all, light from all points of the object must pass through the same column of turbulent atmosphere. This is called the "isoplanatic" requirement, and it has been measured to be about 3–5 arcsec. Consequently, asteroid studies should not be affected by isoplanatic problems. More critically, the Worden *et al.* (1977) correlation method begins to break down when objects approach the seeing limit, 1 arcsec. This may help explain the discrepancy between speckle diameters for Pallas and other values, since Pallas was about 0.7 arcsec in diameter when observed.

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